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Superior Smartphone Display Quality Enhances Viewing Performance and Comfort

Description

Purpose: Visually demanding tasks are performed on Smartphones. Presently most advanced smartphone displays vary in their spatial resolution, luminance, and color rendering. Users of different ages might be differently affected by these properties because of their visual abilities. The present study evaluated effect of these display properties of smartphones on user's viewing performance, viewing discomfort, and subjective preference. **Methods:** Young (age 18 to 30) and old (age 40 to 65) adults were recruited to perform visual detection and reading tasks on three phones with Advance Enhanced In-Plane Switching [AH-IPS] LCD, Pentile matrix [PenTile] OLED, and Vertical strip [VStrip] OLED displays. Their viewing distance and visual performance was measured with a visual discrimination task. Their viewing distance, reading performance, and perceived discomfort was measured with continuous reading. Subjective comparisons of display properties for the tested phones were also conducted with text, photo, and video images. **Results:** LCD resulted in better identification on the Landolt Ring visual acuity test (with fixed target distance) and enabled longer viewing distances in the reading task compared to OLEDs. OLED displays were better in displaying saturated red and blue text, whereas LCD was better in displaying black&white text. Subpixels arranged in vertical strips allow better visual performance and better visual appearance than in the tested PenTile structure. The older group performed more poorly on the Landolt Ring task with fixed viewing distance, but less so for LCD display with self-adjusted distance. **Conclusions:** The present findings demonstrate that higher resolution of LCD compared to OLED displays result in better perceived display quality and performance advantages as measured by human resolution and viewing distance. The increased resolution of the LCD apparently enabled the older group to adjust the viewing distance to attain equal performance with the younger group. These indicate the importance of improving smartphone display quality to enhance the performance for those with greater visual difficulty.

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Superior Smartphone Display Quality Enhances Viewing Performance and
Comfort

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Keywords: Display resolution, screen luminance, subpixel structure, display preference, visual discomfort.

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Abstract

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Conclusions: The present findings demonstrate that higher resolution of LCD compared to OLED displays result in better perceived display quality and performance advantages as measured by human resolution and viewing distance. The increased resolution of the LCD apparently enabled the older group to adjust the viewing distance to attain equal performance with the younger group. These indicate the importance of improving smartphone display quality to enhance the performance for those with greater visual difficulty.

Introduction

Smart phones are increasingly replacing laptop PCs to fulfill the need of mobile computing ¹. To enable multi-media and full-capacity viewing that is visually demanding, significant enhancements have been made to display quality of smart phones in three regards: larger screen size, higher display resolution, and brighter screen luminance ^{1,2}. These have been largely achieved by the deployment of Wide Video Graphic Array (WVGA), and some versions of its augmentations, that allow a larger display area and finer display resolution ³. Improvements in display quality are also facilitated by innovations in video chipset, mobile bandwidth (4th-generation mobile network), and operating systems (e.g., Android, IOS, and Window Phone).

Organic Light Emitting Diodes (OLED) and Liquid Crystal Displays (LCD) are the present leading display technologies for smartphones (Lee, Liu, & Wu, 2008). OLEDs are light-emitting diodes in which the emissive electro-luminescent layer is a film of organic compounds, and do not require a backlight source ⁴. OLEDs emit light in response to electric current conducted between two oppositely-aligned electrodes, with the top one being transparent to permit good light emission. OLEDs typically have a very short response time and consume very low electricity.

LCDs are thin, flat electronic visual displays that use the light modulating properties of liquid crystals (LC). Two oppositely polarized film layers modulate the exiting light generated by a backlight source (⁵). Electric current is applied with two transparent electrodes to alter the orientation of the LC to enable the modulation of display luminance for individual sub pixels. Viewing angle and luminance level of LCD displays are affected by the orientation of LC and electrodes, with luminance and contrast reduced with oblique viewing angles. New technologies, such as In-Plane Switching (IPS) LCD enables wider LCD viewing angles in horizontal and vertical directions by orienting the LC in parallel to the panel surface, but results in reduced perpendicular luminance. Recent improvements in emitted luminance have been made by Advanced Enhanced-IPS (AH-IPS) with higher backlight output ³.

As currently implemented in smart phones, state-of-the-art LCD and OLED displays are different in three important aspects: luminance/contrast level, spatial resolution, and color saturation/balance. AH-IPS LCD displays (utilized by devices such as iPhone 4) currently possess greater luminance, higher display resolution, and better color balance compared to most advanced OLED displays such as Super active-matrix OLED, or Super AMOLED. Super AMOLED in turn has greater color saturation and higher contrast ratio (due to lower black level). Super AMOLED is structured in either PenTile Matrix strips (uneven-sized and intermixed red, green, and blue subpixels) or vertical sub-pixel strips, whereas AH-IPS LCD uses mostly vertical sub-pixels. These contrasting properties may result in significantly different levels of visual performance and comfort for mobile phone users⁶⁻⁹. Currently there is no scientific evaluation and comparison of these two display technologies in relation to their effect on visual performance and visual comfort.

Individual's visual abilities are known to mediate effect of computer display on visual performance and symptoms^{10,11}. Young and old adults are the key population of smartphone users and they are different in their visual abilities: older viewers (> 40 years old) have poorer accommodative ability¹²⁻¹⁷, require higher luminance input¹⁸⁻²⁰, require higher display contrast^{16,21}, and have loss of retinal and cortical neural density²². It is likely older adults are more sensitive to the difference in display qualities of smartphones.

This study investigates the effects of smartphone display on visual performance and comfort. Younger and older viewers were recruited to perform tasks on three smart phones with distinct display technologies: AH-IPS LCD (iPhone 4), Super PenTile Matrix [PenTile] Super AMOLED (Samsung Galaxy S), and vertical strip [VStrip] Super AMOLED (Samsung Galaxy S2). Participants were tested with near-threshold visual stimuli presented in different colors to measure the effect of display resolution and color rendering. Continuous reading was also conducted with different environmental illuminance conditions (50, 500, and 16000 lux) to evaluate effect of screen luminance.

We hypothesized that the LCD displays would be more comfortable on tasks such as reading because of greater resolution and luminance compared to the OLED display, whereas OLED displays would be more preferred in reading color stimuli and in high illumination conditions where their vivid color output and better contrast ratio could be helpful. In addition, the effect of subpixel structure on OLED displays was tested on two OLED devices with VStrip and PenTile sub-pixels respectively. PenTile subpixels should provide poorer display resolution but greater color saturation than VStrip subpixels. Finally, we also asked participants to view text, images, and video clips displayed on the three phones side by side, and reported their subjective preference of critical display qualities.

Methods

Participants

Sixty participants were recruited and assigned to two age groups (young adult: 18 - 30 years, N = 30; older adult: age 40 - 65 years; N = 30). Their visual acuity was 20/25 or better for each eye at both 6M and 40 cm without correction or with habitually worn optical correction. They were native English speakers or with ability to read English fluently, and did not have any previous diagnosis of visual, ocular, or neurological disorders. Participants were recruited from our participant lists (aggregated with permission from previous participants), from University campus, and from the broader community using emails, websites, electronic bulletin boards, and local newspapers. All participants signed a human consent form approved by the Institutional Review Board of Pacific University.

Materials

Viewing Discomfort Questionnaire. Participants' visual and physical discomfort were measured with the Viewing Symptom Questionnaire (VSQ). This questionnaire has been shown to be effective in measuring various types of viewing symptoms^{11,23}. There are 15 questions in VSQ. Each question was displayed on a computer screen, and participant used a computer mouse to indicate their response on an accompanying analog scale.

Reading Materials. Detective stories were formulated into image pages consistent with the size of the opening on the phone holder and displayed in 7-point Calibri font. An adequate number of pages, and corresponding comprehension questions (one question for every 5 pages) were prepared for 45 minutes of reading.

Display Preference Evaluation. At the end of the final testing session, participants were asked to assess the quality of tested displays and their preference. This was achieved by presenting them with text images, still photos, and video clips shown on the three side-by-side displays. After viewing the stimuli, participants answered seven display quality assessment questions by clicking on three separate analog scales to indicate their preference or evaluation for each of these three phones.

Visual Discrimination Stimuli. Landolt C stimuli, calibrated for 40 cm viewing, of logMAR size 0.0 (20/20) with positive polarity (black text on white background) and iso-luminant ones of logMAR size 0.2 (20/32 size, red, green, and blue on gray background) were employed to evaluate the ability to discern static stimuli on tested displays. Performance was evaluated by measuring ability to correctly identify the orientation of the Landolt C opening (4 possible orientations). Iso-luminant stimuli were created by using red, green, and blue foreground color (24, 81, and 5.5 cd/m² screen luminance respectively with 500 lux room illumination) and background gray with matching luminance.

Apparatus

Display devices and Physical Setup. Samsung Galaxy S (PenTile OLED), Samsung Galaxy 2 (VStrip OLED), and iPhone 4 (AH-IPS LCD) were selected to test LCD and OLED display technologies. They were denoted as OLED1, OLED2, and LCD phones respectively. Table 1 shows display properties for these three phones. They were tested with their native display resolution (800 x 480, 800 x 480, and 960 x 640 pixels; 233, 218, & 326 ppi) respectively. All testing stimuli were designed to possess an image size better than 640 x 960 to fully exploit the spatial resolution of the three phones.

-- Table 1 --

The physical size of display area for the three phones was 4.0, 4.3, and 3.5 inches diagonal, and their weights were 4.2, 4.1, and 4.9 oz respectively. The three tested phones were concealed in a black holder (W 8" x H 3.75" x D.58") with an opening of W 2.9" x H 1.9" (3.5" diagonal), from which the central part of the phone screen was shown. This allowed the identity of the device to be masked and the size of display area to be equalized across tested displays. In half of the visual discrimination trials, the device holder was placed on a stand, and a chinrest was used to keep the viewing distance at 40 cm and 15 degree downward angle; in the other half of visual discrimination trials and in all other tasks the participant held the device freely and altered their viewing distance at will. In all tasks, the phone was held in landscape orientation and with both hands.

Viewing Distance Measurements. Viewing distance between the display device and the viewer was captured continuously with a miniature webcam embedded into the casing of the phone holder, with only the lens exposed and aligned slightly to the left of the display (2cm to the left edge of the opening when held in landscape orientation). A custom-written socket program was used to intercept video image at 60 frames/sec and extract facial geometric structure with which viewing distance was calculated.

Visual ability measurements. A digital visual acuity system (Basic Visual Acuity System, M&S Technologies) was used to measure binocular far visual acuity. A paper Snellen chart was used to measure near acuity at 40 cm. Testing stimuli were sized to measure the acuity based on a logMAR (logarithmic minimal angle of resolution) scale. A focusing bead and type were used to measure near point of convergence; a stereo fly chart (%%) was used to measure stereoacuity. Only participants with monocular visual acuity better than 20/25 for both eyes were admitted into the study.

Testing room and Illumination-controlled chambers. A testing room with lighting maintained at 500 lux measured at a viewing height of about 1.2 m was used to conduct the testing of visual discrimination and preference evaluation tasks. In addition, three separate light chambers were constructed

in the room, each 1.7m H x .9m W x 1.2m D in dimension. The illumination levels in those chambers at the viewing height were 50, 500, and 16000 lux. A chair without armrests was placed against the backside of the depth axis to accommodate the participant.

Experimental Procedures

After the participant arrived at the lab for the first test session, a brief description of the experimental procedure and an explanation of the experimental setup were given to him/her. The participant was encouraged to ask any questions s/he might have about the study. Formal consent of the participant was obtained in writing using a consent form approved by the Institutional Review Board at Pacific University. Participants who met the recruitment criteria and signed the consent/assent form were then entered into the experiment.

Each participant was tested in 3 sessions. Each session involved testing with one of the 3 phones. The order of the three testing sessions for each participant was assigned based on Latin Square design and conducted sequentially for each participant, with at least one-day separation between sessions. In all three testing sessions, up to three participants were tested at a time. Each testing session lasted approximately 90 (1st and 2nd sessions) to 120 (3rd session) minutes. Participants were compensated for their time and effort at the end of the third session.

During the first session of the experiment, the participant was screened again based on the inclusion and exclusion criteria and tested with their habitually-worn optical correction. The following specific measures were taken: binocular visual acuity at 40 cm, stereoacuity at 40 cm, near point of convergence, and the amplitude and direction of heterophoria at 40 cm.

For each session, the participant performed the visual discrimination task for 20 mins and reading task for 60 mins. Half of trials in the visual discrimination task were done with a constant viewing distance (40cm) by using desk-mounted phone holder and chinrest; the other half were conducted with the participant freely holding the phone with their viewing distance

continuously measured. Participants' ability to discern details of display content was measured with the task of detecting the orientation of small Landolt C black & white targets (20/20) and iso-luminant color targets (20/32). Target size was selected to be near threshold; iso-luminant color targets were more difficult to discern, hence the larger stimulus size allowed response accuracy comparable to black&white stimuli. Participants had unlimited time to indicate their choice with a keyboard.

After the visual discrimination task, the participant performed the reading task for 60 mins. In each testing session, the same phone was used to display the text content in three illumination conditions (50, 500, and 16000 lux) for 15 mins respectively. Participants' reading performance was measured based on reading comprehension and reading speed. Reading comprehension was measured by the percentage of correctly answered questions related to the content the participant just read. Reading speed was defined as the average number of words read per minute. Immediately before and after reading in each of the three illumination conditions, viewing symptoms were measured with the VSQ. These post-reading measurements took 5 mins for each 15-min reading session. The sequence of reading in each light chamber in the three testing sessions was also counterbalanced based on Latin square design.

In the third session for each participant, in addition to the above tasks, they also viewed the same text, photo images, and video clips (text page, still image, and three 3-min long videos) simultaneously on all 3 phones and afterwards indicated their individual preference/evaluation of the tested phones with the display quality questionnaire. This took about 30 mins.

Data Analysis

Descriptive statistics were conducted to characterize demographics including age and visual abilities (visual acuity, stereoacuity, near point of convergence, and heterophoria). Percentage of correct responses and the means of viewing distance in the visual discrimination task were computed for each testing sessions. Reading speed (words per minute) and reading

performance (correct rate of answering comprehension questions) were also computed, as well as the mean viewing distance for each three-minute interval, resulting in 5 mean viewing distances for each 15 minutes of reading in each of three luminance conditions.

Outcome measures (viewing symptoms, reading comprehension accuracy, reading speed, stimulus discrimination accuracy) were analyzed as a function of phone type, stimulus color, illumination condition, and age using repeated measures ANOVAs and ANCOVAs.

Results

Demographic and Visual Variables

Of the 60 participants finishing all experimental sessions, 38% of them were male and the mean age for the two age groups was 25.3 (SD = 3.8) and 52.7 years (SD = 8.8) respectively. Binocular near visual acuity for young and old participant groups, measured in logMAR (logarithmically transformed minimal angular resolution), was -.08 (SD = .052) and -.02 (SD = .080). Their mean stereoacuity was 29.1 arc-sec (SD = 21.03) and 61.5 arc-sec (SD = 46.06), and their mean near point of convergence (NPC) was 11.0 cm (SD = 5.52) and 11.5 cm (SD = 5.80) respectively.

Viewing Distance

Viewing distance (VD), defined as the distance between the center point of the two eyes and the front surface of phone screen, was measured in visual discrimination and reading. For visual discrimination, repeated measures ANOVA revealed a significant main effect of phone type ($F[2, 48] = 3.289$, $p = .048$), but not stimulus color ($F[3,47] = 1.322$, $p = .175$) nor age ($F[1,49] = 1.809$, $p = .185$). There was no interaction among phone type, color, and age. The LCD phone (44.5 cm) resulted in a significantly farther VD than OLED1 (39.8 cm); OLED2 (43.5 cm) did not differ from LCD and OLED1.

For VD in reading task, there were significant main effects of phone type ($F[2,22] = 3.453$, $p = .050$) and illumination ($F[2,22] = 12.530$, $p < .0001$), but not measurement time ($F[4,20] = 2.264$, $p = .098$) nor age ($F[1,23] = .039$, $p = .845$). There was no interaction among them. VD for LCD (53.3 cm) was

significantly farther than OLED1 (50.4 cm) and OLED2 (50.8 cm). Low illumination (50 lux, 47.6 cm) resulted in significantly closer VD than intermediate (500 lux, 51.5 cm) and high illumination (16,000 lux, 55.3 cm).

Visual Discrimination

With fixed viewing distance (VD) of 40 cm, there were effects of phone type ($F[2,55] = 36.554$, $p < .0001$) and age ($F[1,56] = 7.286$, $p = .009$) for viewing black&white targets, but not the interaction between phone type and age. Participants reported significantly more accurately the orientation of Landolt C with LCD (86.9%) than OLED1 (62.4%) and OLED2 (67.8%). Younger participants reported more accurately (76.5%) than older participants (68.3%).

With self-adjusted VD, there was an effect of phone type ($F[2,52] = 7.792$, $p = .001$), color ($F[3,51] = 45.893$, $p < .0001$), and age ($F[1,53] = 12.947$, $p = .001$). There was also interaction between phone type and age ($F[2,52] = 5.662$, $p = .006$), between phone type and color ($F[6,48] = 35.841$, $p < .0001$), and among phone type, color, and age ($F[6,48] = 4.417$, $p = .001$). LCD (90.0%) and OLED2 (88.1%) phones afforded significantly greater accuracy than OLED1 (83.0%). Black&White (78.2%) resulted in significantly lower response accuracy than red (93.7%), green (86.1%), and blue (90.0%) targets, but this difference is not remarkable because the stimulus size for B&W (20/20) was smaller than color targets (20/32). In addition, red and blue targets resulted in higher accuracy than green targets. Older participants (82.8%) responded significantly less accurately than younger ones (91.2%).

Figure 1 shows the interaction between phone type and age group for the self-adjusted viewing distance condition. It reveals older participants responded less accurately than younger ones with OLED1 and OLED2 (more so with OLED1), with no age difference for the LCD. Among the three phones, LCD resulted in higher accuracy than OLED1 and OLED2 for older participants.

-- Figure 1--

Figure 2 shows the response accuracy relative to phone type and target color where the phones were held freely. For OLED1, red targets resulted in greater accuracy than green and blue targets; for OLED 2, this was also the

case, but all three correct rates were higher and the differences quite small. For LCD, red and green targets resulted in greater accuracy than blue targets. Across the three phones, OLED1 afforded the highest accuracy for red targets among the phones, whereas OLED2 had higher accuracy for blue and LCD had higher accuracy for green. Note that LCD phone resulted in much higher response accuracy for B&W targets than OLED1 and OLED2, and OLED2 higher than OLED1.

-- Figure 2--

There was also a three-way interaction among phone type, color, and age. Essentially the effects depicted in Figure 2 were much more evident for older participants, but not significant for younger participants.

Reading Performance

Three-way repeated measures ANOVA revealed no effect of phone type ($F[2,40] = .189$, $p = .828$), illumination ($F[2,40] = .274$, $p = .762$), nor age ($F[1,41] = .154$, $p = .697$) on reading comprehension. There was no interaction among them.

For reading speed, there was an effect of illumination ($F[2,50] = 3.864$, $p = .028$), but not phone type ($F[2,50] = 1.019$, $p = .368$) nor age ($F[1,51] = 1.849$, $p = .180$). There was also no interaction among them. High illumination (188 words/sec) resulted in significantly greater reading speed than low illumination (177 words/sec), and neither was different from intermediate illumination (183 words/sec).

Viewing Discomfort

Repeated measures ANCOVA was conducted to evaluate the overall viewing symptoms. Logarithmically transformed scores for each symptom were pooled and entered into analysis, and baseline scores obtained at the beginning of the three sessions were also pooled and averaged to serve as the covariate. Results show significant effect of luminance ($F[2,53] = 14.582$, $p < .0001$), but not phone type ($F[2,53] = .152$, $p = .859$) nor age ($F[1,54] = .050$, $p = .825$). There was no interaction among phone type, illumination, and age. High

illumination resulted greater discomfort (18 of 100%) than intermediate (15%) and low illumination (14%).

To explore effects of these variables on individual symptoms, ANCOVAs on individual symptoms were also conducted, with the pre-reading discomfort level serving as a covariate. Significant findings are reported in Table 2; non-significant results are marked with dashes in the table. The noted differences in the table are based on Bonferroni comparison with a family-wise $\alpha = 0.05$.

The table reveals a general effect of illumination level on physical (general physical, tiredness, neckache, headache), visual/ocular (eyestrain, difficulty to visually focus, and double vision), motion sickness (dizziness and disorientation), and cognitive (difficulty to concentrate, think, and memorize) discomfort. High illumination resulted in greater viewing symptoms than lower illumination, and sometimes intermediate illumination. Higher physical/visual symptoms likely resulted from glare and screen reflection, from trying to hold the phone in specific angles to avoid glare, or from vergence difficulty in near viewing. Higher cognitive discomfort likely resulted from the increased processing difficulty due to the glare.

-- Table 2 --

In addition, older participants had more visual (double vision, disorientation, jumping image) and physical (general physical discomfort and neckache) difficulty. Their visual discomfort likely resulted from their difficulty in properly focusing the displayed text content with reduced accommodation due to presbyopia, and their physical symptoms from difficulty in maintaining a good posture with more limited accommodative ability. This is supported by the farther viewing distance they adopted when holding the phone freely, and poorer visual discrimination with a fixed VD.

Display Preference

Repeated measures ANOVA was first conducted to evaluate overall preference by summing the total scores from the seven questions based on the direction of preference (i.e., scores for negative statements were reversed before pooled with those for positive statements). Results show a significant

main effect of phone type ($F[2,55] = 5.749$, $p = .005$) but not age ($F[1,56] = .830$, $p = .366$). There was an interaction between phone type and age ($F[2,55] = 5.181$, $p = .009$). LCD (70.5%) was significantly more preferred to OLED1 (59.2%) and OLED2 (62.6%), and there was no difference in preference between OLED1 and OLED2. Figure 3 shows the interaction between phone type and age. Younger participants preferred LCD to OLED2. Older participants on the other hand preferred OLED1 and OLED2 to LCD.

-- Figure 3 --

Separate ANOVAs were also conducted for individual questions, and the resultant significant effects are summarized in Table 3. The LCD phone was perceived as brighter, with more pleasing color, sharper image, smoother image appearance, and smoother motion than OLED1 and OLED2, and also less flickering than OLED2. Younger participants reported LCD as more preferred than OLED1 and OLED2, and OLED2 than OLED1, whereas older participants reported no difference.

-- Table 3 --

Discussion

The present study compared the performance and comfort afforded by smartphones possessing the most advanced display technologies at the time of testing. The tested display technologies, AH-IPS LCD and Super AMOLED, differ in their screen luminance, display resolution, and color balance/saturation. Table 4 summarizes the present findings. The LCD phone, with brighter emitted luminance and finer spatial resolution than OLED ones, allowed greater discrimination of visual details and farther viewing distances when the stimulus was displayed with the typical black text on white background. Measurements of objective reading performance, not shown in the table, revealed no effect of phone type on reading comprehension and reading speed.

-- Table 4 --

Participant's subjective preference, evaluated after viewing various types of text, image, and video content, reflected additional differences among tested phones. The LCD phone provided an image perceived as

brighter, with more pleasing color, and with smoother image appearance; all of which likely reflected the better spatial resolution and color balance, as noted in Table 3. LCD phone also provided greater sharpness and smoother object motion and less flickering.

Age appears to affect the performance and comfort on different types of phone displays. The older group had poorer entering visual acuity and stereoacuity as measured with clinical tests. Consistent with their reduced visual acuity, the older group also performed more poorly on the Landolt Ring task (with fixed viewing distance) - but only for the OLED displays and not the LCD display. The increased resolution of the LCD apparently enabled the older group to adjust the viewing distance to attain equal performance with the younger group. Older participants also reported greater discomfort in some visual symptoms than young participants. Younger participants discerned visual details more poorly with OLED phones. Consequently, they also liked LCD phones more than OLED phones, whereas old participants preferred OLED phones.

Together, the present findings demonstrate that the differences in display qualities between LCD and OLED technologies for young and old viewers are significant enough to affect visual performance, visual discomfort, and subjective preference.

Display Resolution and Viewing Distance

In the present study, participants reported smoother image appearance and brighter screen for LCD display compared to OLED displays. With fixed, viewing distance, their ability to discern near-threshold Landolt C was also better with LCD. When allowed to adjust their viewing distance freely to detect visual details, participants adopted a closer viewing distance for OLED1 phone than for LCD phone.

Correspondingly, in reading text rendered with supra-threshold font size (7-point font) that is still below the ideal font size (typically 11- to 12-point;

Tai et al., 2010), participants also adopted a closer viewing distance for OLED phones than the LCD phone.

These findings indicating a significant effect of display resolution on human perception, requiring a closer viewing distance in order to discern the visual stimulus^{11, 24-25}. The closer viewing distance likely increased the stress to the accommodative system due to poorer spatial resolution^{7, 11, 26-27}.

These findings cannot be attributed to the difference in display contrast, as the resultant display contrast (> 95%) for the three phones are at levels where its effect on visual processing has largely reached an asymptote²⁸⁻³⁰.

Ambient Illumination, Emitted Luminance, and Visual Comfort

Visual comfort in screen viewing is determined by not only the absolute level of emitted luminance, but also the environmental illumination^{6,7}. All tested phones in the present study had a screen luminance ($\geq 290 \text{ cd/m}^2$ in a dark room) above that measured from printed materials in a typical office setting³¹. However, since mobile phones are often used in a wide range of lighting conditions, the adequacy of screen luminance has to be evaluated accordingly.

To evaluate the effect of emitted luminance from a phone screen and ambient illumination on reading performance, we required participants to read from the three phones in three illumination conditions, low (50 lux), intermediate (500 lux), and high illumination (16000 lux). These conditions simulated the illumination condition in dim living room, in a typical office/classroom, and in a shaded outdoor area.

The results show that operation under higher illumination resulted in longer viewing distances, faster reading speed, and greater discomfort. The longer viewing distances may have been enabled by the assumed smaller pupil size associated with higher room illumination. The greater discomfort is likely due to greater glare from the surrounding room, The faster reading speed for higher illumination may be related to the greater discomfort, as heightened visual discomfort has previously been accompanied by accelerated reading speed^{32,33}. Presumably, discomfort can prompt people to work faster.

Sub-pixel Structure, Color Saturation, and Display Preference

Both LCD and OLED displays render colors by manipulating the luminance output of individual sub-pixels. Our measurements of the tested OLED displays show greater color saturation for blue subpixels relative to the tested LCD display, as shown in Table 1.

Our findings show the LCD phone resulted in better visual discrimination with green targets than OLEDs, whereas OLED1 phone afforded better visual discrimination ability with red targets, and OLED2 with blue targets. This is likely because the green sub-pixels had a lower luminance output compared to the red and blue sub-pixels on the OLED displays.

The present study also show visual details of black&white stimuli were better perceived, and viewing distance was farther with LCD phone than with OLED2 (vertical strips) and OLED1 (PenTile). In reading, LCD phones also resulted in farther viewing distance than OLED1 and OLED2. These reflect the better display resolution of the tested LCD display. The lack of difference between OLED phones is remarkable as the spatial resolution for OLED1 (233 ppi) is actually better than OLED2 (218 ppi). It indicates PenTile sub-pixels are probably not as ideal in rendering fine visual details in black&white images as the typical subpixel structure of even physical size for color subpixels. This is not surprising because the pattern of PenTile sub-pixel arrangement likely increases the perceived aliasing of small visual details resulting in a more jagged perception.

Together, our findings suggest that sub-pixel structure is influential in both objective visual performance and subjective preference. LCD display with vertical strip subpixels and higher resolution offered the best viewing performance and highest preference. OLEDs on the other hand performed better for displaying color details.

Age, Visual Abilities, and Phone Display

The present study recruited two age groups of participant in anticipation of their different visual abilities, and resultant performance and comfort in using smart phones. Young participants between 18 and 30 years are known to

have better ability to accommodate, have higher retinal neural density, and require lower display luminance compared to older participants between 40 and 65 years old ^{12-18,21,34}. These are reflected on the better near binocular acuity and finer stereoacuity for younger participants in the present study ³⁵. Correspondingly and consistent with earlier studies ³⁶, we found older participant reported visual details less accurately with fixated or self-selected viewing distance, especially with OLED phones that have lower display resolution

Interestingly, there was no difference in the preference for the three phones for older users, but a consistent preference to LCD phone for young users. Since for the preference task participants were not demanded to maintain their visual performance as in visual discrimination and reading task, they likely maintained a farther viewing distance due to their reduced accommodation. The lack of phone preference likely reflects older user's inability to appreciate the better resolution at the farther distance.

Conclusions

The present study demonstrated that even with the most advanced display technologies, there are measurable differences in objective visual performance and subjective discomfort and preference. Future display technologies should improve on spatial resolution as well as increase screen luminance while maintaining good color balance and sub-pixel arrangement to optimize user's viewing experiences and productivity.

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References

1. Zheng, P., & Ni, L. (2006). *Smart phones and next generation mobile computing*. Morgan Kauffman: San Francisco, CA.
2. Ballagas, R., Borchers, J., Rohs, M., & Sheridan, J. G. (2006). The smart phone: a ubiquitous input device. *Pervasive computing, IEEE*, 5(1), 70-77.
3. Lu, R., Wu, S.-T., Hong, Q., & Wu, T. X. (2006). Wide viewing angle multi-domain In-Plane Switching LCD. *Mol. Cryst. Liq. Cryst.*, 453, 379-392.
4. Tang, C. W.; Vanslyke, S. A. (1987). Organic electroluminescent diodes. *Applied Physics Letters*, 51(12), 913.
5. Scheffer, T. J. and Nehring, J. (1984). A new highly multiplexable LCD. *Appl. Phys. Lett.*, 48(10), pp. 1021-1023.
6. Lin CC, Huang KC. Effects of ambient illumination and screen luminance combination on character identification performance of desktop TFT-LCD monitors. *International journal of Industrial Ergonomics* 36: 211-218, 2006.
7. Sheedy JE, Bailey IL, Raasch TW. Visual acuity and chart luminance. *Am J Optom Physiol Optics* 61(9): 595-600, 1984
8. Yang SN, Tai YC, Hayes JR, Doherty RA, Corriveau PJ, Sheedy JE. Effects of Font Size and Display Quality on Reading Performance and Visual Discomfort of Developmental Readers. Presented in the annual meeting of American Academy of Optometry, San Francisco: 2010.
9. Ziefle M. Effects of display resolution on visual performance. *Human Factors*: 40: 554-568, 1998.
10. Blehm, C., Vishnu, S., Khattak, A., & Mitra, S., & Yee, R. W. (2005). Computer vision syndrome: a review. *Survey in Ophthalmology*, 50(3):253-62.
11. Tai, Y-C, Sheedy, JE, Hayes, JR, Kundart, JJ. (2008). *Viewing Distance and Visual Discomfort While Using Handheld Displays*. Presented in the Annual Conference of American Association of Optometry. Anaheim, California: October, 2008.
12. Blackwell, OM, and Blackwell, HR. Visual performance for 156 normal

- observers of various ages. *J Illumin Eng. Soc* 1:3-13, 1971.
13. Donders FC. *On the anomalies of accommodation and refraction of the eye: With a preliminary essay on physiological dioptrics*. London: The New Sydenham Society, 1864.
 14. Duane A. Studies in monocular and binocular accommodation, with their clinical application. *Trans Am Ophthalmol Soc* 20: 132-157, 1992.
 15. Kasthurirangan S, Glasser A. Age related changes in accommodative dynamics in humans. *Vision Research* 46(8-9): 1507-1519, 2006.
 16. Suzuki TA, Qiang Y, Sakuragawa S, Tamura H, Okajima K. Age-related changes of reaction time and p300 for low-contrast color stimuli: Effects of yellowing of the aging human lens. *J Physiol Anthropol*. 2006 Mar;25(2):179-87.
 17. Weale RA. Age and transmittance of the human crystalline lens. *J Physiol* 395: 577-587, 1988.
 18. Gerth C, Garcia SM, Ma L, Keltner JL, Werner, JS. Multifocal electroretinogram: age-related changes for different luminance levels. *Graefe's Arch Clin Exp Ophthalmol* 240: 202-208, 2002.
 19. Hecht S. The relation between visual acuity and illumination. *J Gen Physiol* 11: 255-281, 1928.
 20. Riggs LA. Light as a stimulus for vision. Ch. 1 in C. H. Graham (Ed.), *Vision and Visual. Perception* (pp. 1-38). John Wiley & Sons, New York, 1964.
 21. Richards, OW. Vision levels of night road illumination. XII. Changes in acuity and contrast with ages. *AM J Optom Physiol* 43: 313-319, 1966.
 22. Spears PD. Neural bases of visual deficits during aging. *Vision Research*, 33(18), 2589-2609, 1993.
 23. Hayes JR, Sheedy JE, Stelmack JA, Heaney CA. (2007). Computer use, symptoms, and quality of life. *Optom Vis Sci.*, 84(8), 738-44.
 24. Jaschinski W. proximity-fixation disparity curve and the preferred viewing distance at a visual display as an indicator of near vision fatigue. *Opto Vis Sci* 79: 158-169, 2002.
 25. Ni T, Bowman DA, Chen J. Increased display size and resolution improves

- task performance in information-rich virtual environments. Proceedings of graphics interface, 2006.
26. Kubota, S., & Takahashi, M. (1989). Permissible luminance of disturbing reflections of light sources on CRT displays. Japan Illuminating Engineering Society Journal, June, 314-318.
 - Kuntz, J. E., & Sleight, R. B. (1950). Legibility of numerals: The optimal ratio of height to width of stroke. *American Journal of Psychology*, 63, 567-575.
 27. Makous, W. (1998). Optics and photometry. In R. H. S. Carpenter & J. G. Robson (Eds.), *Vision research: A practical guide to laboratory methods* (pp. 1-49). Oxford, England: Oxford University Press.
 28. Blackwell HR. Contrast thresholds of the human eyes. *J Opt Soc Am*, 36: 624-643, 1946.
 29. Legge, G. E., Parish, D. H., Luebker, A., & Wurm, L. H. (1990). Psychophysics of reading. XI. Comparing color contrast and luminance contrast. *Journal of the Optical Society of America A*, 7, 2002-2010.
 30. Legge, G. E., Rubin, G. S., & Luebker, A. (1987). Psychophysics of reading—V. The role of contrast in normal vision. *Vision Research*, 27(7), 1165-1177.
 31. Kaufman JE. IES lighting handbook: The standard lighting guide (Fourth Edition). Illuminating Engineering Society, 1966.
 32. Yang, S.-N., Tai, Y.-C., Hayes, J. R., Doherty, R. A., Corriveau, P. J., & Sheedy, J. E. (2010). Effects of screen luminance and text contrast on reading performance and visual discomfort of developmental readers. Presented in the Annual meeting of American Association of Optometry. November, 2010: San Francisco, CA.
 33. Rempel D, Willms K, Anshel J, Jaschinski W, Sheedy J. (2007). The effects of visual display distance on eye accommodation, head posture, and vision and neck symptoms. *Human Factors*, 49(5), 830-8.
 34. Knoblauch K, Saunders F, Kusuda M, Hynes R, Podgor M, Higgins KE, Monasterio FM. Aged and illuminance effect in the Farnsworth-Munsell 100 hue test. *Appl Opt* 26: 1441-1448, 1987.
 35. Darrock I, Goodman J, Brewster S, Gray P. The effect of age and font size

on reading text on handheld computers. In Costabile MF and Paterno F, Interact 2005, LNCS 3585: 253-266. International Federation for information processing, 2005.

36. Greene HA, Madden DJ. Adult age differences in visual acuity, stereopsis, and contrast sensitivity. Am J Optom Physiol Opt. 1987 Oct;64(10):749-53.

Figure Captions

- Figure 1. Mean correct rate in discerning the orientation of Landolt C in trials where the phones were held freely. Here young group ranges from 18 to 30 years old, old group 40 to 65. Non-overlapping error bars indicate significant difference at $\alpha = .05$.
- Figure 2. Mean correct rate in discerning the orientation of colored Landolt C relative to phone type and target color where the phones were held freely. Non-overlapping error bars indicate significant difference at $\alpha = .05$. B&W targets were smaller compared to colored targets; hence differences and comparisons between B&W and colored targets are not meaningful.
- Figure 3. Overall preference relative to phone type and age group. Higher percentages indicate greater preference. Non-overlapping error bars indicate significant difference at $\alpha = .05$.

Table 1. Display properties of smart phones tested in the present study.

	OLED1 (Samsung Galaxy S)	OLED2 (Samsung Galaxy S2)	LCD (iPhone 4)
Resolution (W x H)	800 x 480	800 x 480	960 x 640
PPI	233	218	326
Screen Size (Diag.)	4.0 in	4.3 in	3.5 in
Weight			
Net weight	4.2 oz	4.1oz	4.9 oz
Holder + camera	6 oz	6 oz	6 oz
Display Method	Super AMOLED	Super AMOLED Plus	AH-IPS LCD
Emitted Luminance	298 cd/m ²	290 cd/m ²	415 cd/m ²
Black luminance	~ 0 (not measurable)	~ 0 (not measurable)	.81 cd/ m ²
Chromaticity	X = .89 *, Y = 1, Z = 1.22	X = .88, Y = 1, Z = 1.2	X = .96, Y = 1, Z = 1.21

* Chromaticity ratios were measured with a white page and computed by dividing measured x, y, z values with measured overall luminance.

Table 2. Effects of phone type, age, and illumination level on viewing symptoms.

	Phone Type	Illumination	Age	Interaction
Physical Discomfort	--	High > Inter,Low	Old > Young	--
Glare	--	High > Inter,Low	--	--
Tiredness	--	High > Inter,Low	--	--
Eyestrain	--	High > Inter,Low	--	--
Headache	--	High,Inter > Low	--	--
Disorientation	--	High,Inter > Low	Old > Young	--
Blurred vision	--	--	--	--
Difficulty in visual focus	OLED1 > LCD	High > Low	--	--
Dizziness	--	High > Low	--	--
Double vision	--	High > Low	Old > Young	--
Jumping image	--	--	Old > Young	--
Neckache	--	High > Low	Old > Young	--
Sleepiness	--	--	--	--
Difficulty to Concentrate	--	High > Inter,Low	--	Phone x Illum
Difficulty to think	--	High > Low	--	--
Difficulty to remember	--	High > Inter,Low	--	--

Table 3. Subjective preference on different properties of tested smartphones.

	Phone Type	Age	Interaction
Brighter screen	LCD>OLED2>OLED2	Young>Old	--
More pleasing color	LCD>OLED2>OLED1	Young>Old	Young: LCD>OLED2>OLED1
Comfortable color	--	Young>Old	--
Sharper image	LCD>OLED2>OLED1	--	Young: LCD>OLED2>OLED1
Smoother image	LCD>OLED2>OLED1	--	Young: LCD>OLED2>OLED1
edge			
Smoother motion	LCD>OLED2>OLED1	--	Young: LCD>OLED2>OLED1
Less flickering	LCD>OLED1,OLED2	--	Young: LCD>OLED2>OLED1

Table 4. Summary of present findings on viewing discrimination, viewing distance, reading discomfort, and display preference. Only significant findings were reported in the table.

Visual Discrimination		
	Fixed VD	Self-adjusted VD
Viewing Distance	--	LCD > OLED1
Accuracy		
Phone type	LCD > OLED1, OLED2	LCD, OLED2 > OLED1
Age	Young > Old	Young > Old
Color	--	Red, Blue > Green
Age x Phone	--	Young: LCD, OLED2 > OLED1 Old: LCD > OLED1, OLED2
Color x Phone	--	B&W: LCD > OLED2 > OLED1 Red: OLED1 > OLED2 > LCD Green: LCD > OLED2 > OLED1 Blue: OLED2 > LCD > OLED1
Reading Performance		
	Viewing Distance	Discomfort
Phone	LCD > OLED1, OLED2	--
Illuminance	High, Inter > Low	High > inter, Low
Age	--	Old > Young
Display Preference		
Phone	LCD > OLED1, OLED2	
Age x Phone	Young: LCD > OLED1, OLED2	

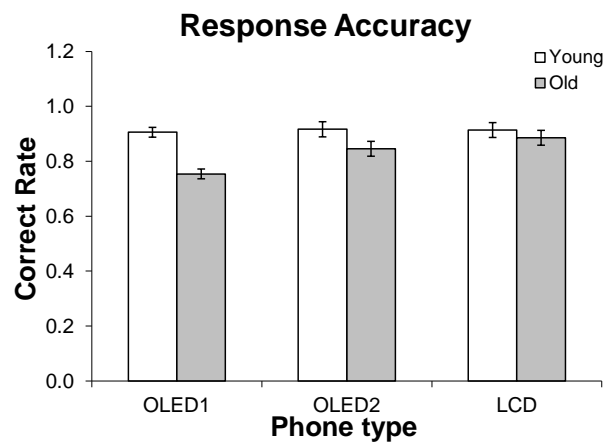


Figure 1

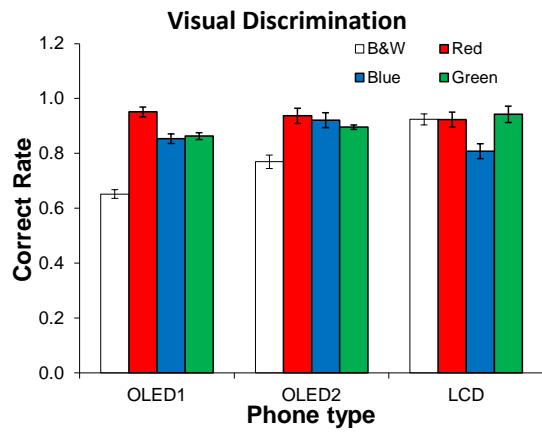


Figure 2

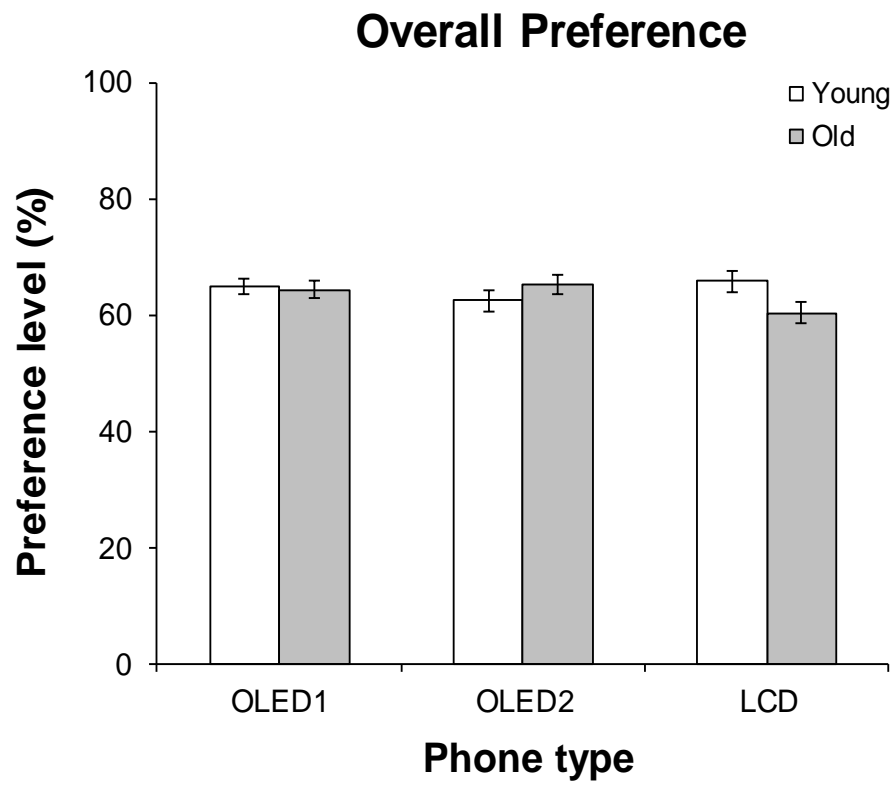


Figure 3